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Nanoscale heat transfer due to near field radiation and nanofluidic flows

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14. ABSTRACT
We have developed techniques for making individual “nano-pipes” with diameters in the range 20-500 nm and lengths of 20 microns. The nanopipes are fabricated by etching single ion tracks in either polymer or mica sheets. We have developed and calibrated mass spectroscopic methods to measure the flow of gases and liquids through the nanopipe over a wide range of temperature. We have identified transitions from laminar to turbulent flow, and from ballistic to hydrodynamic flow in the smallest pipes ever investigated. Because of the vacuum conditions at the low pressure end of our nanopipes, liquid flows through the pipe would spontaneously form a liquid/vapor interface either inside the pie or near the exit. We developed a model which describes the details of this process; this type of complex flow in evaporative refrigerators and in evaporation from porous media. All of our measurements can be accounted for assuming a slip length of zero, i.e. we see no anomalous flow in the nano regime. To further explore the role of slip, we have investigated the flow of superfluid helium 4. In superfluid, the flow velocities can exceed 10m/sec , and in distinct contrast to classical flows, the flow rate is essentially independent of pressure. We have also constructed a custom apparat

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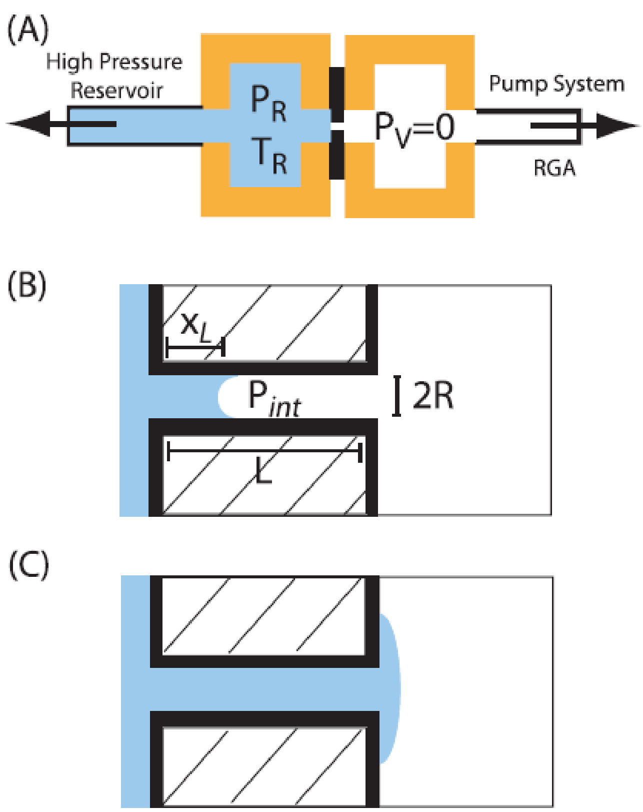
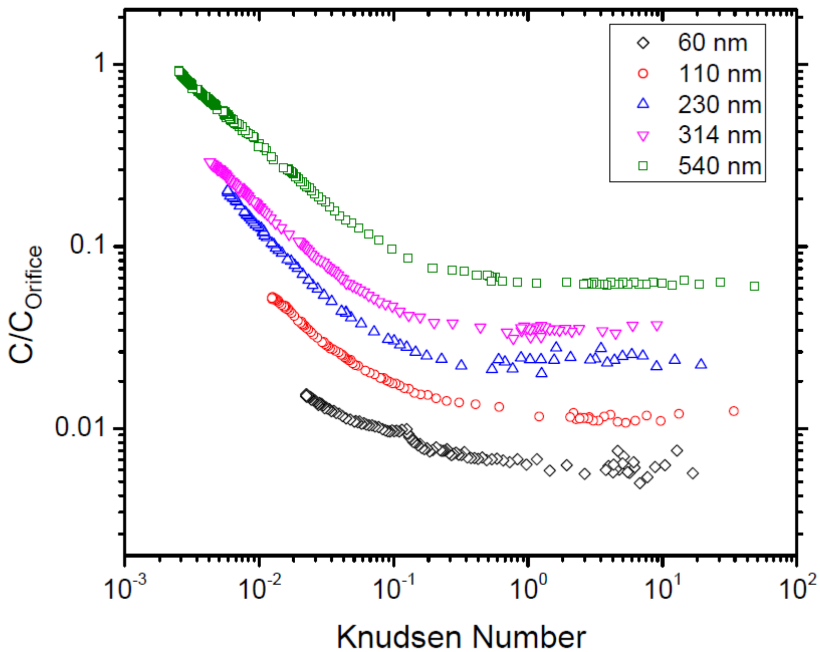
Final report on FA9550-12-1-0065 : Nanoscale heat transfer due to near field radiation and nanofluidic flows, Peter Taborek, Department of Physics and Astronomy, UC Irvine

Thermal management is a crucial issue in the design of electronic systems which is becoming increasingly important as device size shrinks and power densities go up. This project addressed two aspects of heat transfer at the nanoscale. The first involves fluid flow through nanometer diameter tubes , which has been suggested as a strategy for making heat exchangers in a sublayer directly below high power density electronics. This strategy provides very high heat transfer coefficients, but requires a pumping system to compensate for the viscous loses in the small tubes. Calculation of these losses depends critically on the boundary conditions for flow at the tube wall. The conventional macroscopic hydrodynamic assumption is that the flow velocity at the wall is zero, or equivalently, the slip length is zero. Recently, there have been a number of experiments on flow through arrays of carbon nanotubes that suggest that the slip length may be in the micron range, which would imply very low viscous losses ; this would obviously enhance the efficiency of heat exchangers made from nanopipes. One of the main goals of our work was to measure the slip length as a function of tube diameter.

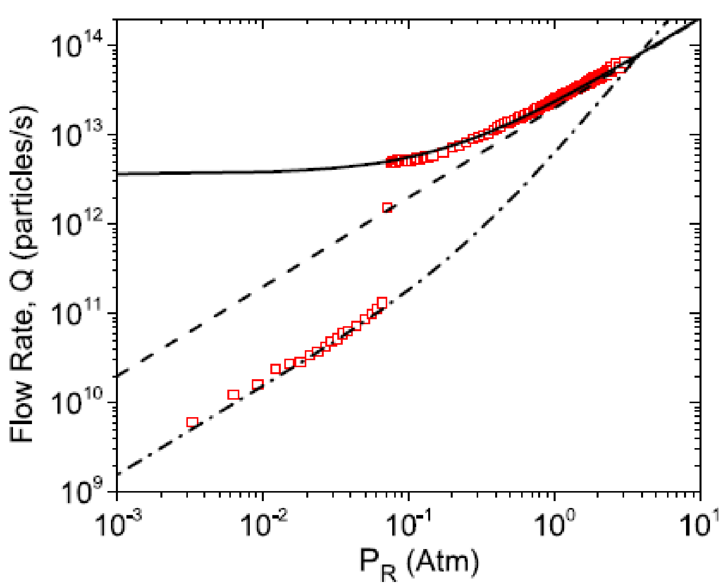
The flow impedance of a tube depends on the radius R to a power R^n , where n can be in the range of 2-4 depending on the details of the flow regime. Because of the high powers involved, experiments on ensembles of tubes with a range of diameters can be quite misleading, so we developed methods for making single nanopipes and measuring the spectacularly small flow rates through them. The methods are described in detail in Velasco et al Phys Rev E 86 ,025302 , but briefly, we obtained from our collaborators wafers of PET or mica which have had precisely one high energy gold ion passed through it. When the wafer is exposed to a reactive etchant, the ion damage track etches preferentially to form a nanopipe whose diameter can be controlled by etching time. The wafer is sealed into a cell that is attached to a pumping system with a mass spectrometer and a fluid handling system. The mass spectrometer serves as a mass flow monitor which is capable of detecting flows as small as 10^6 molecules/sec. The flows through the nanopipes are so small that diffusion through the wafer can be a comparable source of mass transfer. To suppress diffusion, most of our measurements were done at low temperatures. The basic form of the apparatus is shown in the figure on the left, which shows a high pressure reservoir at pressure P_R and a vacuum section connected to the residual gas analyzer (RGA) mass spectrometer. The two sections are connected with a membrane with



a single nanoscopic channel. We carefully calibrated our mass spectrometer using known macroscopic flow impedances and NIST traceable mass flow sources. Our first measurements focused on the transition between rarefied gas flow and hydrodynamic flow in a gas. The Knudsen number Kn is the ratio of the mean free path to the diameter of the tube. In the rarefied gas regime, the conductance c goes like R^3, while in the viscous hydrodynamic regime, the conductance goes like R^4; the transition is clearly seen in the figure below.

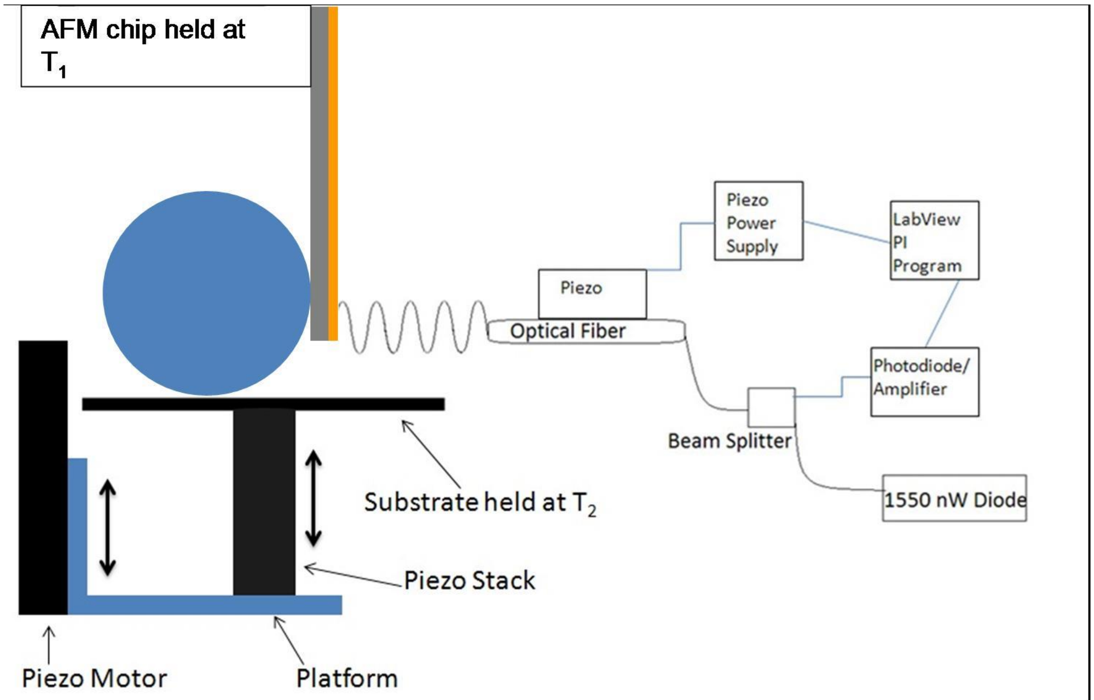


When the pressure in the upstream reservoir is increased beyond the saturated vapor pressure of the fluid, liquid forms in the pipe. As this happens, there is an abrupt increase in the mass flow through the pipe, as shown in the figure below. Mass flow through a pipe is proportional to the pressure drop across the pipe, which is confirmed by the data in the lower branch which shows a linear relation with slope of 1. In the upper branch, in which liquid is flowing through the nanopipe, the relation between flow rate and pressure drop is nonlinear. This is due to the large effects of the Laplace pressure across the liquid/vapor interface in the nanopipe, which is inversely

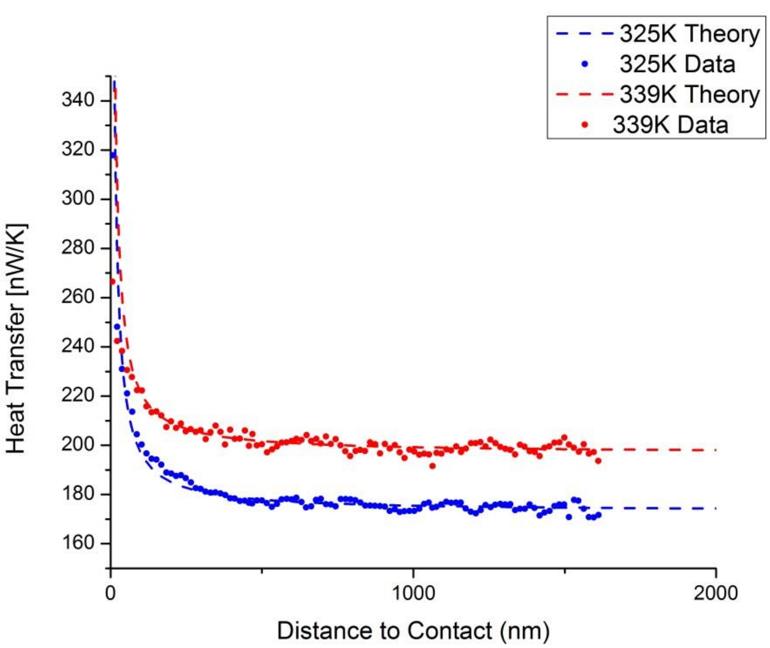


proportional to the pipe radius. We have developed detailed models which account for all of these effects and can be used to predict the pressure drops in two phase flows in nanopipes.

The other heat transfer issue we investigated was near field radiation. We built a custom apparatus



shown in the Figure above. The main features are a vertically mounted cantilever with a 100 micron diameter glass or sapphire sphere bonded to the end. The base temperature of the cantilever is held at temperature T1, while the substrate temperature is held at temperature T2. The distance between the sphere and the substrate can be controlled with piezo motors at the nanometer level. As the temperature of the sphere increases , the cantilever bends. The bending is monitored with an optical fiber interferometer. The entire apparatus is in high vacuum. The bending can be calibrated by measuring the radiative heat transfer at distances much larger than the thermal wavelength (10 microns) where classical radiation formulas apply. As the distance between the sphere and the substrate is reduced to less than 1 micron, the radiative heat transfer rises dramatically, as shown in the figure on the left. The measured data are in good agreement with theoretical calculations shown by the dashed curves.



Both of these projects are still on-going. We have developed a technique to measure flow of water at room temperature through nanopipes and are continuing to study the issue of slip in nanoscale channels. We hope to be able to extend these studies to the limiting case of carbon nanotubes. We are trying to measure the systematics of the temperature dependence of near field radiation as a function of temperature; at low temperature, the effects should extend to larger distances because the thermal wavelengths are longer. This project supported most of the thesis work of Angel Velasco, who is currently a post doc at JPL. It also helped to support the thesis work of Robert Joachim, who will graduate in about one year. Angel, Robert and I are very grateful for the support of the AFOSR.

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Abstract

We have developed techniques for making individual “nano-pipes” with diameters in the range 20-500 nm and lengths of 20 microns. The nanopipes are fabricated by etching single ion tracks in either polymer or mica sheets. We have developed and calibrated mass spectroscopic methods to measure the flow of gases and liquids through the nanopipe over a wide range of temperature. We have identified transitions from laminar to turbulent flow, and from ballistic to hydrodynamic flow in the smallest pipes ever investigated. Because of the vacuum conditions at the low pressure end of our nanopipes, liquid flows through the pipe would spontaneously form a liquid/vapor interface either inside the pie or near the exit. We developed a model which describes the details of this process; this type of complex flow in evaporative refrigerators and in evaporation from porous media. All of our measurements can be accounted for assuming a slip length of zero, i.e. we see no anomalous flow in the nano regime. To further explore the role of slip, we have investigated the flow of superfluid helium 4. In superfluid, the flow velocities can exceed 10m/sec , and in distinct contrast to classical flows, the flow rate is essentially independent of pressure. We have also constructed a custom apparatus to measure radiative heat transfer between two solids separated by a vacuum gap in the nanometer range. The device utilizes a silicon nitride cantilever with a gold coating with a 100 micron diameter sphere attached to the end. Temperature gradients in the cantilever cause

deflection because of the differential thermal expansion of the materials . The deflection is measured with nanometer accuracy using an optical fiber interferometer.

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Flow and evaporation in single micrometer and nanometer scale pipes, A.E. Velasco, C. Yang, Z.S. Siwy, M.E. Toimil-Molares, and P. Taborek, Appl. Phys. Lett 105, 033101 (2014)

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